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DESIGNING AN ADVANCED INSTRUCTIONAL DESIGN ADVISOR: COGNITIVE SCIENCE FOUNDATIONS (VOLUME 1 OF 6)

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The Advanced Instructional Design Advisor (AIDA) is an R&D project being conducted by the Armstrong Laboratory's Human Resources Directorate aimed at producing automated instructional design guidance for developers of computer-based instructional materials. The process of producing effective computer-based instructional materials is complex and time-consuming. Few experts exist to ensure the effectiveness of this process.

As a consequence, the Air Force is committed to providing its courseware developers with up-to-date guidance appropriate for the creation of computer-based instruction. This guidance needs to be firmly gounded in cognitive learning theory. In addition, the assistance should be provided in an automated setting to ensure that the entire process is as efficient as possible. This technical paper addresses the cognitive foundations for instructional design guidance.

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PREFACE

The work reported herein was done for the Advanced Instructional Design Advisor project at the Air Force Armstrong Laboratory (ALHRD -- formerly AFHRL). The substance of this research was done under contract to Mei Associates, Inc., the primary contractor on the Advanced Instructional Design Advisor (Contract No. F33615-88-C-0003).

This work was done as part of the first phase effort on the Advanced Instructional Design Advisor. The initial phase of this project established the conceptual framework and functional specifications for the Advanced Instructional Design Advisor, an automated and intelligent collection of tools to assist subject matter experts who have no special training in instructional technology in the design and development of effective computer-based instructional materials.

Mei Associates' final report for the initial phase is being published as an Armstrong Laboratory Technical Paper. In addition, Mei Associates received 14 papers from the seven consultants working on this phase of the project. These 14 papers have been grouped into 6 sets and edited by ALHRD/IDC personnel. They are published as Volumes 1 - 6 of Designing an Advanced Instructional Design Advisor:

Volume 1: Cognitive Science Foundations

Volume 2: Principles of Instructional Design

Volume 3: Possibilities for Automation

Volume 4: Incorporating Visual Materials and Other Research Issues

Volume 5: Conceptual Frameworks

Volume 6: Transaction Shell Theory

This is Volume 1 in the series. Dr. J. Michael Spector wrote Sections I and IV. Dr. Robert D. Tennyson wrote Section II. Dr. Martha C. Polson wrote Section III.

SUMMARY

The Advanced Instructional Design Advisor (AIDA) is an R&D project being conducted by the Armstrong Laboratory's Human Resources Directorate in response to an Air Training Command (ATC) Manpower, Personnel, and Training Need calling for improved guidelines for authoring computer-based instruction (CBI) (MPTN 89-14T).

Aggravating the expensive and time-consuming process of CBI development is the lack of Air Force personnel who are well-trained in the areas of instructional technology and educational psychology. More often than not, a subject-matter expert with little knowledge of CBI is given the task of designing and developing a computer-based course. Instructional strategies that work in a classroom are often inappropriate in a computer-based setting (e.g., leading questions may work well in a classroon but are difficult to handle in a computer setting). Likewise, the computer offers the capability to present instruction in ways that are not possible in the classroom (e.g., computer simulation models can be used to enhance CBI).

The AIDA project is aimed at providing subject-matter experts who have no background in computer-based instructional systems with automated and intelligent assistance in the design and development of CBI. The goal is to reduce CBI development time while ensuring that the instructional materials are effective.

I. INTRODUCTION (Spector)

The Advanced Instructional Design Advisor is an R & D project aimed at providing automated and intelligent assistance to inexperienced instructional designers who have the task of designing and developing computer-based instruction (CBI). The particular problem being addressed by this line of research is the need for more cost efficient methodologies for the design and development of CBI. Current methods for developing CBI are expensive, time-consuming, and often result in ineffective instruction due to the general lack of expertise in computer-based instructional systems (Spector, 1990).

The Advanced Instructional Design Advisor project is divided into four phases:

Phase 1: Conceptualization & Functional Specifications

Phase 2: Conceptual Refinement & System Specifications

Phase 3: Prototype, Field Test, & Refinement

Phase 4: Technology Demonstration & System Validation

The first two phases have been funded with Task Order Contracts. The third phase is being performed under a Broad Agency Announcement (BAA). The fourth phase will be completed via a fully specified contract. The work reported herein concerns the first phase.

As part of the conceptualization of the Advanced Instructional Design Advisor, the consultants and project scientists agreed that the behavioral foundation of Instructional Systems Design (ISD) was not adequate as a basis for the design of instruction, since ISD ignored the contributions that cognitive science has made to learning theory in the last several decades. As a result, it was further agreed that a set of tools designed to assist novice instructional designers in the development of CBI should be firmly grounded in a cognitive theory of learning.

The next two sections of this paper outline a cognitive framework appropriate to the conceptualization of an Advanced Instructional Design Advisor. Section II represents a succinct summary by Robert D. Tennyson of a cognitive model of learning. While there may be minor disagreement about terminology, the model presented below is widely accepted and informs much of the later development of the Advanced Instructional Design Advisor.

Section III is an elaboration by Martha C. Polson of some of the general implications of such a model for the design of instruction. While Polson notes the lack of a general and unified theory of cognition, she provides numerous insights concerning particular aspects of cognition that have instructional implications. These insights inform many of the principles of instructional theory presented in the second volume in this series.

There is much agreement in these two chapters in spite of slight differences in terminology. For example, Tennyson identifies these three types of knowledge: declarative, procedural, and contextual. Polson discusses declarative, procedural, and causal knowledge. The difference is in the third category. Tennyson's contextual knowledge includes knowing when and why other knowledge is appropriate. Polson's causal involves knowing why some other knowledge is correct or appropriate. It is clear from Polson's discussion, however, that she interprets 'why' broadly enough to encompass Tennyson's contextual type.

What is clear from these two chapters is that a cognitive model of knowledge should inform the process of designing instruction. Polson's chapter and subsequent volume in this series begin to elaborate the implications of accepting this axiom.

II. COGNITIVE MODEL OF LEARNING AND COGNITION (Tennyson)

Introduction

This section contains an overview of a learning and cognition model. This model forms the basis for a proposed update of the standard Instructional Systems Design (ISD) model (see Volume 2 in this series). Several earlier discussions of this model can be found in the literature (Tennyson, 1981; Tennyson & Breuer, 1984; Tennyson & Cocchiarella, 1986).

Figure 1 shows that the acquisition of knowledge comes from both external and internal sources. This is an important concept for prescribing cognitively oriented instructional strategies, because most behaviorally oriented instructional practices assume that new knowledge comes only from external information sources. Under the cognitive view of learning, it is necessary to consider instructional strategies that include direct reference to internal cognitive processes of knowledge acquisition and employment, as well as ones that rely only on external sources (Anderson, 1980, 1982). The basic components of this cognitive system model include the following: sensory receptors, perception, short-term and working memory, and long-term memory.

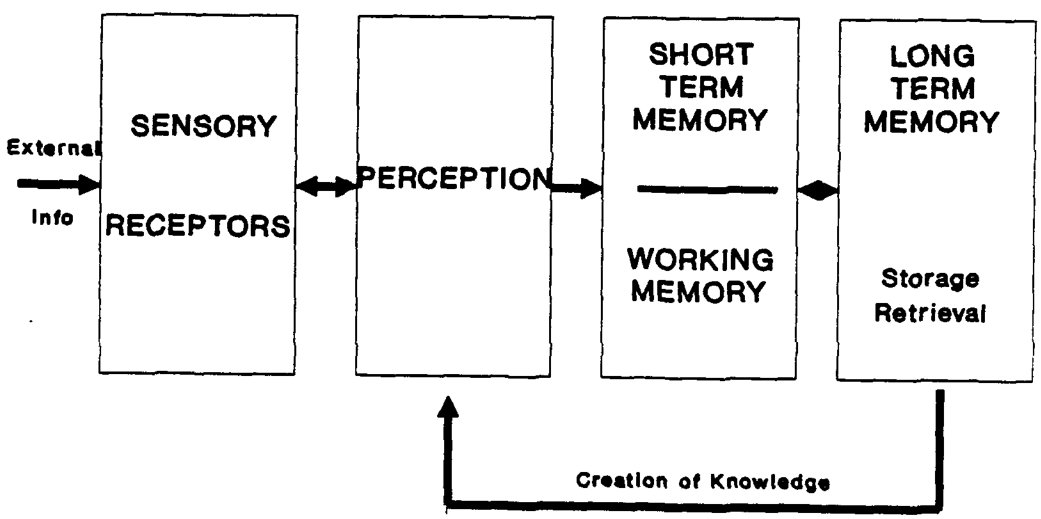

Figure 1. Cognitive System

Sensory Receptors

This component includes the various ways in which external information is input into the cognitive system. Basically, these receptors are the learner's ears, eyes, and skin. External stimuli include text materials, visuals, and audio sources.

Perception

Information coming from either external or internal sources passes through the perception component, which performs the functions of being aware of and assessing the potential value of the external or internal information. Thus, the perception component serves the purposes of both attention and effort in cognitive processing (Dorner, 1983).

Short-term and Working Memory

The next component consists of two forms of memory that only deal with immediate cognitive processes: short-term and working memory. Short-term memory is defined as having a limited capacity in which information is maintained for the given moment (actually, for only a few seconds). Working memory, on the other hand, involves conscious effort or metacognitive awareness of the encoding process between itself and long-term memory (Brown, Armbruster, & Baker, 1984).

Long-term Memory

The acquisition of information and the means to employ information occurs with the storage and retrieval subsystems of the long-term memory component (see Figure 2) (Tennyson & Breuer, 1984). Within the storage subsystem information is encoded the knowledge base according to various formats, while the cognitive abilities to employ the knowledge are in the retrieval subsystem.

Knowledge Base

The storage system is where coded information is assimilated into the existing knowledge base. A knowledge base can be described as an associative network of concepts (or schemata) which vary per individual according to amount, organization, and accessibility of its information (Rabinowitz & Glaser, 1985). Amount refers to the actual volume of information coded in memory; organization implies the structural connections of that information; accessibility refers to the executive control strategies used in the service of thinking (i.e., recall, problem solving, and creativity). The latter two forms of knowledge (organization and accessibility) are those that separate an expert from a novice. That is, a large amount of information is not the key to expert thinking. The key to expert thinking is the ability to find and employ information appropriately.

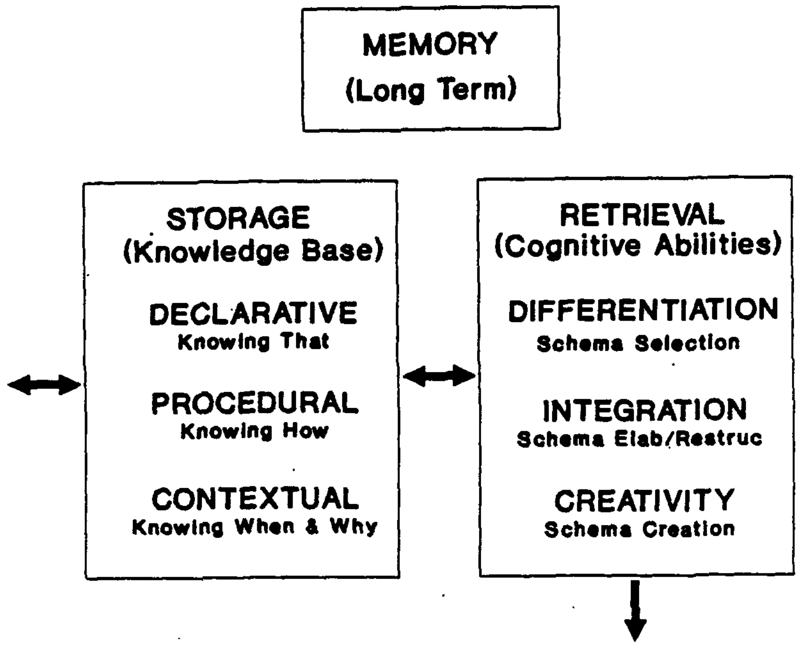

Figure 2. Memory

Types of Knowledge

Within storage, there are various types of knowledge: declarative, procedural, and contextual (Shiffrin & Dumais, 1981). Each type represents a different memory system component or function. Declarative knowledge implies an awareness of information and refers to the "knowing that," for example, underlining keywords in a text will help recall. Procedural knowledge implies a "knowing how" to use given concepts, rules, and principles. Contextual knowledge implies an understanding of "knowing when and why" to select specific concepts, rules, and principles. This executive control process of knowing when and why is governed by selection criteria embedded within the organization of the knowledge base. Selection criteria are the values and situational appropriateness by which connections within the schematic structure of a knowledge base are made. Whereas both declarative and procedural knowledge form the amount of information in a knowledge base, contextual knowledge forms its organization and accessibility.

Cognitive Abilities

The retrieval system employs the cognitive abilities of differentiation (i.e., selecting) and integration (i.e., restructuring) in the service of the thinking strategies of recall, problem solving, and creativity (see Figure 2). The operational term for the retrieval systems functions of differentiation and integration is <u>cognitive complexity</u> (Schroder, 1971). Differentiation is defined as follows:

(a) the ability to understand a given situation.

(b) the ability to apply appropriate contextual criteria (i.e., the standards, situational appropriateness, and/or values) by which to selectively retrieve specific knowledge storage.

Integration is the ability to elaborate or restructure existing knowledge in the service of the given problem situation. Creativity is the ability to form new declarative and procedural knowledge as well as contextual knowledge by using the total cognitive system.

Thinking Strategies

For purposes of this section, there are three categories of thinking strategies, ranging in order of cognitive complexity. The first category, recall strategies, employ only the automatic selection (i.e., differentiation) of knowledge directly as stored in memory. Problem solving strategies, on the other hand, require both cognitive abilities of differentiation and integration. These strategies are formed at the time of solution and are stored as contextual knowledge. That is, problem solving strategies represent knowledge of knowing when and why to select specific items of declarative and procedural knowledge. Furthermore, they are domain specific and cannot be considered as generic skills that can be transferred between domains. Therefore, the accumulation of problem solving strategies in the knowledge base occurs in direct reference to the number of problems solved within given domains. Creative strategies, in addition to employing differentiation and integration, make use of the cognitive ability to create knowledge not already coded in memory (Dehen & Schank, 1982).

Summary

In summary, all three kinds of thinking strategies (recall, problem solving, and creativity) are acquired while using the cognitive abilities of differentiation, integration, and creation. Each strategy form is embedded by domain within the contextual knowledge structure of the knowledge base. Therefore, as the learner engages in more thinking situations, the individual thinking strategies become increasingly more abstract and generalizable within the domain (Sternberg, 1985). This overview of a learning and cognition model forms a theoretical backdrop for the development of an Advanced Instructional Design Advisor and for an updated ISD model.

III. COGNITIVE THEORY AS A BASIS FOR INSTRUCTION (Polson)

Introduction

The goal of this section is to summarize theoretical results from cognitive science that are relevant to the Advanced Instructional Design Advisor. The particular goal is to prescribe a "knowledge theory" which is relevant to instructional design. The approach I will take is to summarize current work on knowledge representation. The consensus in the area of cognitive science is that intelligent action is produced by processes that operate on complex knowledge structures. Our task is to understand the knowledge necessary to perform relevant skills and then to ask how such knowledge structures might be acquired.

Unfortunately, there is not a single unified theory of cognition that I can draw on for these relevant theoretical implications. Two investigators have the announced intent of formulating a unified theory of cognition: John Anderson with his A* theory (Anderson, 1983), and Allen Newell with his SOAR system (Laird, Newell, & Rosenbloom,1987; Newell, 1987). Of these two, Anderson has made a serious effort to delineate the educational implications of his theoretical approach, particularly with respect to how procedural knowledge (i.e., knowledge of how to perform a task) is acquired.

Newell has concentrated more on developing a theory which accounts for performance of cognitive and motor tasks, than on understanding the acquisition of knowledge necessary to perform the tasks. From an educational standpoint, however, both of these theories have serious gaps in coverage and are in disagreement on certain issues. For instance, neither theory seriously addresses the issue of how facts (declarative knowledge) are acquired. Also, the educational role of regulation or control of knowledge and the awareness of the contents of one's knowledge (metacognition) are not well developed in these theories. These less well developed aspects must be drawn from other theories or approaches which are less comprehensive than those of Anderson and Newell, but cover more thoroughly these particular aspects of cognition (Palinscar & Brown, 1984; van Dijk & Kintsch, 1983; Kintsch, 1988; Kintsch, 1989). The account presented here is, therefore, more of a synopsis than a unified theory.

The major current theories of cognition and knowledge arise from the cognitive science perspective. Many of the major concepts and assumptions, both implicit and explicit, which underlie the approach are directly relevant to instructional design and differ radically from earlier approaches. Only a brief discussion of these issues for the purpose of orienting the reader will be given here. For those interested in a more thorough discussion, an excellent, very readable account of the history of the field of cognitive science and a delineation of its major assumptions can be found in Gardner (1985). Phye and Andre (1986), Estes (1988) and Glaser (1989) also provide an excellent overview of why the current approaches are more relevant to everyday human learning and performance and how they differ from the earlier behaviorist approaches that dominated the field of learning prior to 1950. Two edited volumes which honor Herbert Simon and Robert Glaser, who are both pioneers in the field, are also excellent sources for work which highlights aspects of current knowledge theory that are relevant to instructional design (Klahr & Kotovsky, 1989; Resnick, 1979).

The view of human cognition that dominates the last 30 years of theory development and research draws heavily on the concept of information processing. This view is articulated by Card, Moran, & Newell (1983):

> A computer engineer describing an information processing system at the system level (as opposed, for instance, to the component level) would talk in terms of memories and processors, their parameters and interconnections. The human mind can also be described as an information processing system and a description of the same spirit can be given for it. (p. 24)

In the information processing approach, the processing of information during learning, cognition, and performance is viewed as an active, not a passive process, that occurs in stages. Some processes occur in parallel and others occur serially. Each stage of information processing is thought of as having its own memories, processors, and types of representation. The two units of this information processing system that are pertinent to this discussion are working memory and long-term memory. Working memory, the active subset of memory, is limited in capacity and requires active processing to maintain information. Long-term memory, which is our store of previously acquired knowledge, can be thought of as being of unlimited capacity and does not require active processing to maintain its knowledge.

One goal of the theories using the information processing approach is to explain how information acquired at one point is transformed and organized within this information processing system, such that it can be retrieved at a later point for use. Equally important is an understanding of why information fails to be encoded, or, if encoded, fails to be retrieved or not retrieved in a usable form. For the theories to be relevant to instructional design they have to provide guidance on how to design instruction to foster the encoding of the information in a manner that facilitates its retrieval in a form useful in the context of performing a given task.

That purposive human behavior is rational and goal oriented is another key concept in current theories of cognition. This view point is expressed by the rationality principle of the principals of operation for the Model Human Processor outlined by Card, Moran, & Newell (1983):

> Rationality Principle. People act so as to attain their goals through rational action, given the structure of the task and their inputs of information and bounded by limitations on their knowledge and processing abilities:
>
> goals + task + operators + inputs + knowledge + processing limits --> behavior (p. 27)

This emphasis on goal directed behavior is particularly apparent in the accounts of the acquisition and use of procedural knowledge, but also plays an important role in the acquisition of declarative knowledge and the comprehension of verbal information, as well as the use of that information.

The emphasis on the active, strategic nature of the information processing approach is another concept that has primary importance for instructional design. This aspect of the approach is in particular contrast to the earlier behaviorist views of learning where the active participation of the learner in the event was not considered important. From the information processing approach, learning is a matter of using strategic processing to encode and organize information so that it can be retrieved at the appropriate time for use. How the information is encoded or represented during that processing to form one's knowledge base is of prime importance in understanding the implications for instruction.

Representational Systems

A theory of knowledge must be based on how knowledge is represented. Issues of representation of knowledge play a key role in all theories of memory and cognition. Details of how knowledge is stored, retrieved, and used are involved in nearly every aspect of memory and cognition. The educational implications of the theories of cognition discussed here follow directly from their view of how knowledge is represented. Gardner (1985) states the importance of mental representations as follows:

> To my mind, the major accomplishment of cognitive science has been the clear demonstration of the validity of positing a level of mental representation: a set of constructs that can be invoked for the explanation of cognitive phenomena, ranging from visual perception to story comprehension. Where forty years

ago, at the height of the behaviorist era, a few scientists dared to speak of schemas, images, rules, transformations, and other mental structures and operations, these representational assumptions are now taken for granted and permeate the cognitive sciences. (p. 383)

A large number of the educational implications of a given theory follow directly from its view of how knowledge is represented. An excellent review of memory representation is given in Rumelhart and Norman (1988). Representational systems in a theory of cognition or knowledge need to capture the most salient psychological aspects of human knowledge. Rumelhart and Norman summarize these as follows:

* The associative nature of knowledge.

* The notion of knowledge units or packages, so that knowledge about a single concept or event is organized together in one functional unit.

* The detailed structure of knowledge about any single concept or event.

* The everyday reasoning of people, in which default values seem to be substituted for information that is not known explicitly, in which information known for one concept is applied to other concepts, and in which inconsistent knowledge can exist.

* The consideration of different levels of knowledge, each level playing a different organizational role, with higher order units adding structure to lower order ones (adapted from Rumelhart & Norman, 1988, p. 523).

The major types of representational systems with known educational implications will be described briefly. Most theories of cognition and knowledge are hybrids using more than one type of representation.

<u>Definition of Representational Systems</u>

A representation system maps the events in a represented world to a representing word in such a manner that the representation mirrors <u>some</u> aspects of the world which is being represented. For instance, a representation of the heights of individual using the set of symbols {<,>,=} to signal less than, greater than, and equal, could tell us which of two individuals was the tallest, but not the absolute difference in their heights. If height was represented by either line lengths or numbers, then absolute differences would be available. A representational system includes not only the representation itself, but processes for interpreting the representations. These processes are as important as the representations themselves. If height is to be represented by lines or numbers, then there must be some process of comparing the lengths of the lines or interpreting the numbers to arrive at the height comparisons.

Types of Knowledge Represented. A number of different ways to classify the knowledge types in term memory have been proposed. A traditional approach has been to classify knowledge as declarative (knowing what), procedural (knowing how), and causal (knowing why). The current theories of cognition that are candidates for comprising a unified theory of cognition do not always divide the contents of long-term memory into exactly those categories. The distinctions among these types of knowledge may be made either on the basis of the way the knowledge is represented or on the basis of the processes that operate on the representations.

Anderson (1983) postulates two distinction memory types in long-term memory: declarative memory and production memory. Declarative memory is represented as associative net in the form of a tangled hierarchy. The nodes or cognitive units of that hierarchy are propositions, spatial images in analogical representation, and temporal strings. Procedural knowledge is represented as productions in productions memory. Declarative and production memory interact through processes that operate on the contents of working memory. The distinction between these two types of long-term memory and their interaction in working memory is the key to his A* theory. His prescriptions on instructional methods and his intelligent tutoring systems are all based on this representational system (Anderson, Boyle, Farrell, & Reiser, 1984; Anderson, 1987).

A description of knowledge that cuts across representational types is the concept of mental model or situation model. In this terminology, to learn about something, to come to understand it, is to construct a mental model. Mental models may have as elements structures which are in any of the representational types. Genter and Stevens (1983) and Johnson-Laird (1983) are a good source for description of much of the work in this field. From the mental model approach, learning is viewed as successively transforming a naive mental model of a given situation into a series of increasingly more conceptually complete models that are adequate for a larger set of problems.

An instructional program developed by White and Frederiksen (1986) to teach troubleshooting uses this increasingly complex mental models approach. White and Frederiksen emphasize qualitative models that teach causal knowledge. Each model incorporates declarative knowledge as well as procedural knowledge and control structures that determine how the knowledge is used. Glaser and Bassok (1989) provide a discussion of the educational principles underlying this approach.

Types of Representations

Meaning: Propositional Representation. The term proposition and propositional representation as these psychological investigators use it does not have exactly the same meaning as a proposition in philosophy. The various propositional representations used by psychologists and AI researchers differ somewhat in terminology and structure, but the underlying differences are relatively minor and generally not of theoretical importance. The terminology and framework of Kintsch and his colleagues is adopted hereafter to illustrate this type of representation (Kintsch & van Dijk, 1983; Turner, 1987).

A proposition represents a single idea or cognitive unit (van Dijk & Kitsch, 1983; Anderson, 1983). Each proposition contains a predicate followed by its arguments. A predicate asserts a relationship among its arguments. For instance the predicate visit, would have the arguments of agent and object. A predicate can be represented as a frame which includes a set of slots for its arguments. The frame for the predicate visit would be visit[agent, object]. The propositional representation of the sentence, Mike visited the Alamo, would be: visit[mike,alamo]. The argument for a predicate can be another predicate. The sentence, Mike visited the Alamo in San Antonio, would have the predicate frame visit[agent,object,location] with the argument location being another proposition:

P1: visit[mike, alamo, P2]
P2: location:in[San Antonio].

The meaning of the concepts which fill the argument slots can be represented in either a propositional form themselves or in an associative net, which better captures some of the psychological aspects of the concepts. Kintsch's theory of discourse comprehension (van Dijk & Kintsch, 1983; Kintsch, 1988) has several layers of propositional representations which are connected in associative or semantic nets in memory.

Semantic nets, scripts, and schemata. Although it is widely agreed that propositions represent the units of meaningful knowledge, they are not useful notations to describe larger highly organized knowledge structures that are employed to represent complex concepts, routine sequences of events and actions, and plans. Other types of representations have been developed for representing these type of knowledge structures.

A semantic net represents knowledge as a series of interconnected nodes with the connections having directed, labeled values (which are in some respects equivalent to the predicates in the propositional approach just discussed). The nets may be represented as graphs (Quillian, 1968; Kintsch, 1988), or they may be presented in outline form (Rumelhart & Norman, 1988). In the simplest of the associative nets, the nodes are concepts with the connections being relations. The nodes are directed because the associations may not be of equal strength in both directions. For instance the word river is more likely to elicit the association bank than the word bank is to elicit the association river. Figure 3 shows a semantic net for the various meaning of the word bank (Kintsch, 1988, p. 165).

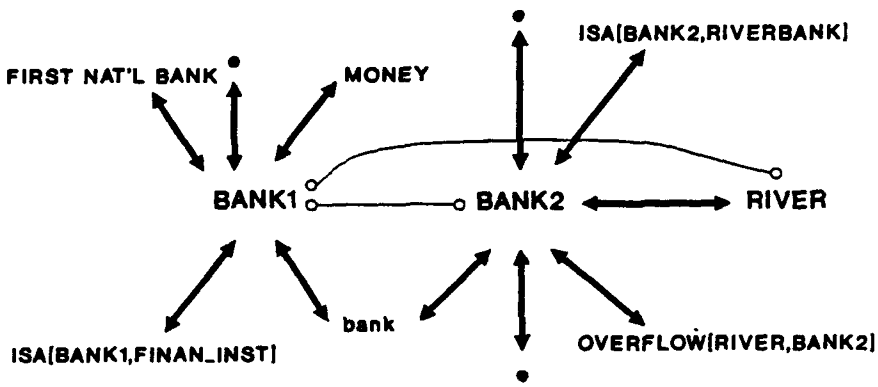

Figure 3. Semantic Net for 'Bank'

In some current theories of cognition (Kintsch, 1988; Anderson, 1983) the cognitive units of an associative or semantic net can themselves be other representational types, such as the propositions just discussed or other higher order structures.

One of the major advantages of the semantic net representation is the ease of representing hierarchies such as those that characterize category information. Figure 4 shows the semantic net representation of parts of the concepts animal, bird, and person (adapted from Norman and Rumelhart, 1988, p. 525):

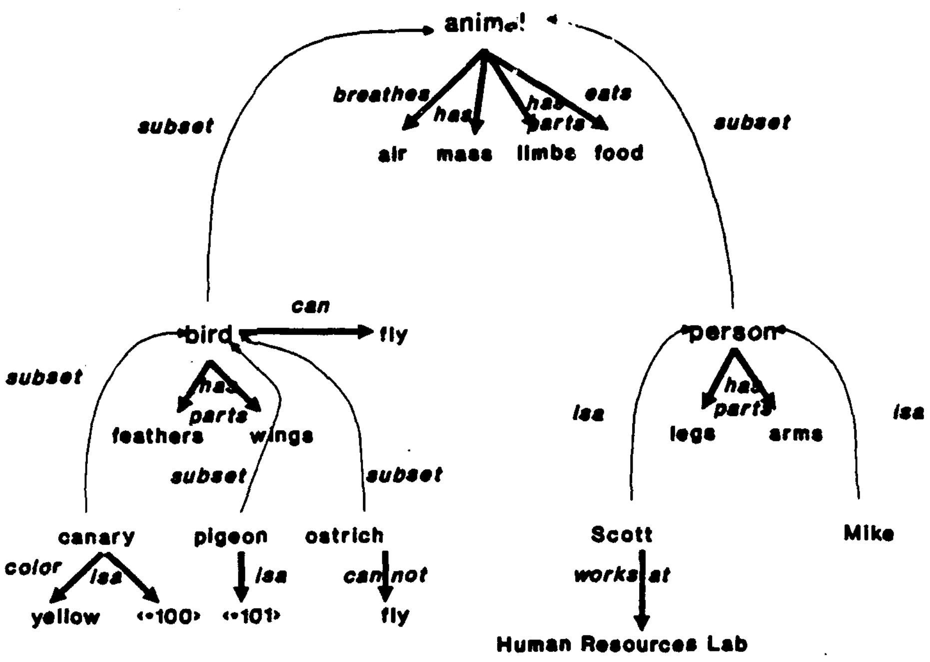

Figure 4. Semantic Net for 'Animal'

These hierarchies allow for default type reasoning and classification and the inheritance of features as well as the existence of contradictions. If a feature is specified in a superordinate concept and there is not a contradictory relationship in the concept of interest, then the feature is assured by default to apply to the concept. The fact that in general birds can fly, but ostriches don't is easily represented as can be seen in Figure 4.

<u>Schemata, Frames, Scripts, Plans.</u> The associative nets account for the associative nature of knowledge, the default inheritance of features, and the structured nature of concept knowledge, while the propositional representations capture the meaning of single ideas. Higher order representational systems such as schemata (Rumelhart & Ortony, 1977; Rumelhart & Norman, 1977; Rumelhart, 1988) and scripts and plans (Schank & Abelson, 1977; Schank, 1980) were developed to account for higher levels of structure in human knowledge.

Schemata, scripts, etc. can be used to represent individual concepts, such as the concept animal, or more complicated knowledge, such as our knowledge about the order and type of events that take place when we go to a restaurant or a grocery store. Schemata, frames, scripts, etc., like propositions, can be thought of as a frame with slots for variables. Schemata will be described as an example of this type of representational system. A given schema frame contains fixed parts and variable parts. Thus, a fixed part of the schema for horse would be Has-Four-Legs. Fixed parts for bird would be Has-Feathers. For both concepts Color would be a variable. Schemata, like propositions, can be embedded within one another to provide very complicated structures which represent large bodies of interrelated knowledge.

The evaluation of schemata in the processing of knowledge is an active process in which incoming information is evaluated for fit, variables are bound, etc. If there is an appropriate fit to the schemata, then that schema is activated. The data that a schema evaluates is both top-down, in that superordinate schemata give input as to the degree to which their information is relevant, and bottom-up, in that information from subschemata input information about how well they account for the information being evaluated. Having representational structures with higher levels of structure and organization accounts for the structured nature of human knowledge in which higher level structures and lower level structures both play a role in the knowledge evaluation and construction that is going on in any one level.

Procedural representation. In a procedural representation, knowledge is represented as a set of actions. Motor acts and skills, such as how to ride a bike, are the most obvious behaviors to be represented in a procedural representation, although cognitive skills, such as how to code a L1SP function, are equally amenable to being represented as procedures (Anderson, Boyle, Panell, & Reiser, 1984). One major difference between declarative and procedural knowledge which must be captured in the representational systems is that the conscious access which we seem to have to declarative knowledge, does not appear to be available for procedural knowledge. We can explain why banks are related to money, but we cannot tell someone how to ride a bicycle or what motor actions are involved in pronouncing the word serendipity.

Production systems. Productions systems are the most prevalent form of procedural representation used in psychology and are a form of pattern directed system. See Waterman and Hayes-Roth (1978) for a through coverage of productions and other pattern directed systems. Newell is primarily responsible for their introduction into modern psychology and artificial intelligence. His theory of cognition (SOAR) uses productions as the primary representational system (Laird, Newell & Rosenbloom, 1987; Newell, 1987). Anderson (1983) makes productions systems the core of his theory of skill acquisition in his ACT* theory.

A production is a recognize-act or condition-action cycle. It can also be thought of as an if-then statement of the sort:

1F (condition-for-triggering) THEN (do-these-actions).

As an illustration of this type of representation the following are the first three productions of a production system for doing addition from Anderson (1984, p. 8):

P1 IF the goal is to do an addition problem
THEN the subgoal is to iterate through the columns of the addition problem.

P2 IF the goal is to iterate through the columns of an addition problem and the rightmost column has not been processed
THEN the subgoal is to iterate through the rows of that rightmost column and set the running total to 0.

P3 IF the goal is to iterate through the columns of an addition problem and a column has just been processed and another column is to the left of this column
THEN the subgoal is to iterate through the rows of this column and set the running total to carry.

Productions can be conceived of as compiled representations of knowledge which are not accessible to introspection. When new "macro" productions are learned, which compile several previous productions involved into an action in one single production, all the intermediate steps are lost. In contrast, the structure of our knowledge represented in the propositional or semantic network representations is open to inspection. This is the basis of our metacognitive knowledges. In fact, to a large degree our acquisition of knowledge is governed by inspecting, comparing, modifying, adding to, and subtracting from these knowledge structures. In contrast to the unlabeled connections in a production system, the nature of the connections play a key role in our use of the other types of knowledge structures.

Control Structures and Processes

In an information processing approach there exist control processes and structures which guide the processing of information. Included in this category is metacognitive knowledge. Awareness of one's own cognitive processing governs the modification of the knowledge base in expert knowledge acquisition. Self-regulatory processes, such as monitoring the processing of knowledge and progress toward a solution of a problem, the comprehension of written material, etc. are examples of metacognitive control processes.

Expert-novice Differences in Knowledge Structures

In the past 25 years, the focus of cognitive research has been on the analysis of complex skills, rather than on how they are acquired. Cognitive task analysis of complex skills has probably been one of the most important contributions of cognitive science to instructional design. Glaser and Bassok (1989) analyzed cognitive research in three areas for their relevance to learning: 1) the acquisitions of procedural skill, 2) self-regulatory and performance control strategies in expert performance, and 3) the acquisition of organized structures of knowledge; they concluded that ". . . it is apparent that the single most important contribution to date of the knowledge and methodology of cognitive science to instructional technology has been the analysis of complex human performance (p.662)."

One important aspect of the analysis of complex skills for instructional design has been the exploration of the differences between the knowledge structures of experts and those of novices (e.g., Chase & Simon, 1973; Simon & Simon, 1978; Ericsson & Staszewski, 1989). Glaser (1989) gives a very succinct account of the implications of these differences for instructional design.

With increasing expertise, the knowledge structures in long-term memory become more interconnected and organized into larger integrated chunks of information rather than isolated fragments. This allows not only larger chunks of information to be retrieved from memory and held active in working memory to be processed, but larger amounts of information can be stored in long-term memory from working memory in a given amount of time. The goal of instruction should be to promote coherent, interrelated, well structured knowledge units which are highly accessible. For any given field of instruction, then, the first task must be an analysis of the knowledge structures of the expert, so that the instructional goals can be aimed at promoting the correct knowledge structures. However, it should be noted that the learner has to play an active role in the building and interconnecting of his knowledge base. Such complex structures cannot be passively imparted (Ericsson & Staszewski, 1989; Resnick, 1989).

Elements of a Unified Theory of Cognition

In this section I review two well developed theories of cognition: 1) the construction-integration model of discourse comprehension of Kintsch and his colleagues (Kintsch & van Dijk, 1978; Kintsch, 1988), and 2) the ACT* theory of Anderson (Anderson, 1984). These theories are based on the knowledge structures and processes that I have just outlined. Both emphasize their educational application. They are complimentary in that the emphasis of the Kintsch model is on how declarative knowledge structures are acquired, while the Anderson theory has been used to model the acquisition of procedural knowledge. When the elements and the emphasis of the two are combined they contain much of the information that would make a strong start toward a complete theory of knowledge. Each is committed to developing computer-based training systems that are based on the principles of their theory of knowledge. Anderson advocates the use of intelligent tutoring systems and has already built several tutors. Kintsch promotes the use of "nonintelligent" tutoring systems that leave the control of learning to the student, but provide scaffolding to support inexpert processing. He has only recently begun his efforts at educational applications in the form of computer assisted training.

Kintsch's Model of Discourse Comprehension

In adults, much of our knowledge is acquired through discourse either from written text or spoken dialogue such as lectures, etc. The fact that knowledge has been acquired from a discourse is demonstrated through some use of that knowledge, providing answers to questions, providing summaries or paraphrases, solving problems which require the use of that knowledge, etc. The comprehension and acquisition of knowledge from these situations is referred to as discourse comprehension.

Discourse comprehension according to the theoretical model of Kintsch and van Dijk (1978) and van Dijk (1983), consists of a hierarchy of strategic processes which operate on successively more complex units of the text. The outcome of each strategic operation is a mental representation in memory. Thus, local-level microprocesses operate on surface features of the text, deriving the meaning from graphemes, words, syntactic patterns, and organizing it into a connected list of propositions. Middle-level coherence processes are gap-filling inferences that complete the meaning of the propositional microstructure, for example, by connecting pronouns to their referents, establishing the identity of coreferents, and filling in unstated relationships within and between propositions.

Microprocesses are higher-order processes that operate on the filled-in microstructure, forming a generalized representation of the meaning at different levels of importance. Other inferential processes may further elaborate the content and serve to integrate it into the reader's own knowledge background. These interpretive processes result in a network memory representation of the situation described by the text which is termed the situation model in van Dijk (1983). Successful reading comprehension thus results in a hierarchical network of macropropositions that represents the gist of the content, and the reader's conceptual understanding of that content. In fact, research on the role of higher-level comprehension processes in meaning suggests quite strongly that these processes may form another stumbling block to the development of expert skill (Perretti, 1985).

While this theory was originally developed to understand the comprehension of discourse, it has recently been extended to understanding how comprehension failures play a role in the application of the knowledge, particularly problem solving. This model has been extended to children's word arithmetic problems. These problems are very difficult for children to solve even if they know the mathematical procedures involved (Kintsch & Greeno, 1985). This work shows that many of the difficulties in solving word arithmetic problems are comprehension problems that result from the construction of an inadequate knowledge representation. There is a mismatch between the model of the problem produced in the process of forming the textbase, the problem model, and the known mathematical procedures. From this Kintsch has concluded that the instructional strategy which should underlie tutoring word problems should be focused on using the situation model as a mediator between the representation of the meaning and the representation of the problem space (Kintsch, 1989).

Under development is a computer-based tutoring system for word algebra problem solving, ANIMATE, that is based on an extension of the discourse computer model (Kintsch, 1988; Nathan & Kintsch, 1989; Kintsch, 1989). This tutoring system is aimed at aiding the student in developing a representation or situation model of the problem which goes beyond the textual information which may not be adequate for problem solution without additional inferences. This tutor is not intelligent in that it has no model of the specific problem being addressed nor does it have a specific model of the knowledge the student has. The idea behind this "nonintelligent" approach is to provide scaffolding of learning rather than planning and monitoring the student's progress. With this tutor students can construct a graphical problem model which drives a computer simulation of the situation. Students can compare the resulting animation to their internal situation model in order to evaluate and alter the problem model. It has been argued that systems which let the student do the planning and monitoring, rather than doing it for them, promote the development of self regulatory skills which characterize expert performance (Bereiter & Scardamalia, 1989; Collins, Brown, & Newman, 1989; Brown & Palincsar, 1989).

<u>Anderson ACT* Theory: Acquisition of Proceduralized Skills</u>

Anderson (1983, 1987) has the broadest theory of cognition in which there has been a serious attempt to relate the theoretical principles to acquisition of proceduralized skills. This application of his A* theory is very nicely elucidated in his annual review paper (Anderson, 1987).

Productions are the key element of Anderson's view of skill acquisition. Cognitive skills are modeled by a set of productions which are hierarchically arranged. Productions both form the cognitive units and the hierarchical goal structure that organize the problem solving. Working memory contains the knowledge that is available at the time. When a new goal, such as "solve this algebra problem" is established by some external event, then this goal becomes active in working memory. If this goal is the condition part of an established "macro" production for solving that type of problem which exists in production memory then that production will be applied and a solution generated to the problem. However, if a known solution does not exist, then a search must begin for a solution. The assumption is made that people solve novel problems by applying weak-problem solving to the declarative memory that they have about this domain. These weak-problem solving solutions include analogy, means-ends analysis, working backward, hill climbing, and forward search (Newell & Simon, 1982).

Which weak method will be used is determined by what declarative knowledge exists about the domain. As the problem is solved by successively searching through declarative memory for the necessary conditions, a trace of the hierarchically organized productions is produced. The learning mechanism is a compilation process that creates efficient domain specific productions from this trace. Proceduralizaton is the first aspect of this compilation process. As the production trace is generated in the production memory, it is now no longer necessary to search declarative memory for the conditions, therefore they no longer have to be held in working memory, thereby reducing it processing load. The next stage is compilation. The series of productions are compiled into a single production which accomplished the same task. Compilation speeds up performance considerably. This compiled production is now available to produce solutions to future problems of this nature.

Anderson has developed intelligent tutoring systems for LISP and Geometry that are based on this account of learning (Anderson, Boyle, Farrell, & Reiser, 1984). These tutors have been very successful. In fact, the LISP tutor is one of the few intelligent tutors which evaluation has shown to be successful. As an instructional tool, these tutors do have the drawback of needing a problem domain which is closed and formal or highly constrained in some way.

Conclusion

The two theories outlined above embody the characteristics of knowledge outlined in this section. For each, attempts have been made to derive instructional principles and apply them in a computer-based training program. However, this is only a small step towards having a unified or even synthesized theory of knowledge and other cognitive processes that can be directly applied to instructional design. Glaser and Bassok, after reviewing three classes of studies and educational approaches that were purposely based on cognitive principles, concluded the following (1989):

> The design of instruction in the studies we have reviewed relies more on models of competent performances in specified areas of knowledge and skill than on models of how this performance is acquired. Anderson's work is the most rigorous in explicitly attempting to use instruction to test a theory of learning. But, in general, assumptions about learning, not well-specified theory, are loosely connected to instructional principles. (p. 662)

While this conclusion does not bode well for the development of a unified theory of cognition that can be applied to the development of instructions, Glaser and Bassok were not entirely pessimistic:

> An evolution of instructional theory and the learning theory that underlies it will come about by investigations of questions that emerge from work of the kind we have described here. Progress in an area is often made on the basis of instrumentation that facilitates scientific work, and, at the present time, a significant tool is the design of instructional interventions that operationalize theory in the form of environments, techniques, materials, and equipment that can be carefully studied. These investigations can be testing ground for new theories of learning and instruction that will benefit both the practice of education and the advance of science. (Glaser & Bassok, 1989, p. 662)

IV. CONCLUSION (Spector)

Effective instructional design should be based on the best available psychological research available, which includes much of the recent work in the area of cognitive science. The research findings summarized in this paper indicate some general consensus about the structure of knowledge and the resulting implications for learning and instruction. However, there is as yet no general unified theory of cognition which accounts for all learning. Much research in cognitive science remains to be done.

Both Tennyson and Polson agree that the organization and accessibility of knowledge are key features in acquiring expertise. Tennyson emphasizes the need to attend to the student's internal cognitive processes when designing instruction. Polson argues that a system which allows students to perform some planning and monitoring promotes the development of regulatory skills essential for expert performance. As a result, in order to be effective, CBI must be highly interactive and the interactions must be designed around appropriate knowledge structures.

There is also much agreement about the three types of knowledge: declarative, procedural, and contextual/causal. Tennyson argued briefly that thinking strategies, a kind of contextual knowledge, are acquired in conjunction with the cognitive abilities of differentiation, integration, and creativity in particular domains. Polson reviewed two computer-based instructional methodologies, one directed at declarative knowledge and a second directed at procedural knowledge.

In addition to its implications for the Advanced Instructional Design Advisor, Tennyson's cognitive model has implications for the ISD process (see Volume 2 in this series). Polson's elaboration of the incomplete nature of cognitive theory will be put sharply in focus in Volume 4 with an attempt to conceptualize an advising system for the use of graphics in courseware.

Subsequent volumes in this series assume the general cognitive framework presented in the previous two sections. Indeed, a central tenet of the design and development process for the Advanced Instructional Design Advisor is that a cognitively oriented learning theory should play a key role in the design of instruction.

In conclusion, what we have seen in the previous two sections is a good starting point for rethinking how we design instruction, especially instruction to be developed and delivered using computers. As Glaser has indicated, a well-conceived research tool can carry us a long way toward our goal of a more complete understanding of the processes of knowledge acquisition and learning, which, in turn, will enable us to design more effective instruction.

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